Enhancing Radiocarbon Chronologies of Colonization: Chronometric hygiene revisited

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Enhancing Radiocarbon Chronologies of Colonization: Chronometric hygiene revisited

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ABSTRACT

Accurately dating when people first colonized new areas is vital for understanding the pace of past cultural and environmental changes, including questions of mobility, human impacts and human responses to climate change. Establishing effective chronologies of these events requires the synthesis on multiple ^{14}C dates. Various 'chronometric hygiene' protocols have been used to refine ^{14}C dating of island colonization, but they discard up to 95% of available ^{14}C dates leaving very small datasets for further analysis. Despite their foundation in sound theory, without independent tests we cannot know if these protocols are apt, too strict or too lax. In Iceland, an ice-core dated tephrochronology of the archaeology of first settlement enables us to evaluate the accuracy of ^{14}C chronologies. This test demonstrated that the inclusion of wider range of samples for ^{14}C dates in Bayesian models improves the precision, but does not affect the model outcome. Therefore, based on our assessments, we advocate a new protocol that works with a much wider range of samples and where outlying ^{14}C dates are systematically disqualified using Bayesian *Outlier Models*. We show that this approach can produce robust *termini ante quos* for colonization events and may be usefully applied elsewhere.

1. Introduction

This paper advocates a new protocol for synthesizing multiple ^{14}C dates that utilizes a much wider range of ^{14}C samples than currently accepted within strict applications of 'chronometric hygiene'. Our approach is rigorously tested using independent chronological controls provided by ice-core dated tephrochronology.

The development of AMS ^{14}C dating meant that very small samples can be analysed which, combined with a lower unit cost, has resulted in the generation of very large datasets of individual age determinations relating to major historical (Bronk Ramsey 2010) and archaeological events, such as the colonization of large islands (Rieth et al. 2011; Williams 2012; Rull 2016). However, more dates do not necessarily result in improved clarity, as with a large dataset ambiguities can multiply with the production of significant numbers of anomalously younger and older dates. These anomalies may occur when samples are poorly provenanced, not directly related to the archaeological event of interest, or have considerable inbuilt age (Bronk Ramsey 2009a). Other outliers may have no obvious explanation for their status because, for example, they are not published with sufficient detail to evaluate these concerns or establish whether methodological protocols were appropriate (Millard 2014; Bayliss 2015; Wood 2015).

These challenges were realised early in the history of radiocarbon dating (Waterbolk 1971), and in response numerous protocols have been developed to help evaluate the quality of ^{14}C dates in large datasets, and to eliminate dates that are most likely problematic, a process which has been subsequently described as 'chronometric hygiene' (after Spriggs 1989). One of the early protocols used in the Pacific rejected large numbers of dates that were considered uncertain because of issues with stratigraphic and archaeological context and material types (Anderson 1991; Spriggs and Anderson 1993). Subsequently, this approach has been extended by other chronometric hygiene protocols that favour using only short-lived plant materials and terrestrial bone (e.g. Rieth et al. 2011; Wilmshurst et al. 2011). The number of different protocols has increased (e.g. Pettitt et al. 2003; Rodriguez-Rey et al. 2015) and each protocol has been used to date colonization events. Significantly, the analysis has become increasingly selective and may reject up to 95% of available ^{14}C analyses (e.g. Rieth et al. 2011). Despite their foundation in sound theory, without independent tests we cannot know if these protocols are apt, too strict or too lax. We aim to test new outlier detection capabilities of the Bayesian software package OxCal (Bronk Ramsey 2009a; Dee and Ramsey 2014). In particular, we want to know if bone samples affected by marine reservoir effects (MRE), such as omnivorous animals and humans with marine diets (e.g. including marine mammals, fish and shellfish) and seaweed eating sheep in coastal area can be used in accurate analysis. If this greater range of materials can be used to create chronologies, synthesized dates may become more precise, and dating may be applied more widely, especially for questions relating chronology in coastal areas and on small oceanic islands.

Iceland provides a remarkable opportunity to evaluate the utilization of large ^{14}C datasets because 513 ^{14}C dates are related to the abrupt 9th century AD Norse colonization that can also be dated independently of the ^{14}C method using an exceptional tephrochronology tied to dates from both medieval written sources and the Greenland ice cores. The crucial Landnám Tephra Layer (LTL) constrains the initial settlement of Iceland, is found across virtually the whole island, and has a combined ice-core date of AD 877 ± 1 (Grönvold et al. 1995; Zilinski et al. 1997; Schmid et al. 2017a). While there is abundant archaeological evidence of settlement immediately above the extensive LTL on a countrywide scale, there are sparse anthropogenic activities below this isochron in the southwest of Iceland (Fig 1). Two turf-built enclosures or boundary walls are recorded just below this tephra demonstrating that people created shelters before this volcanic eruption (Jóhannesson and Einarsson 1988; Roberts et al. 2003; Schmid et al. 2017b). Significantly, no ^{14}C samples related to archaeological evidence in stratigraphic contexts have been found below the LTL. Later tephra isochrons help to refine the rate and scale of Viking Age settlement: these include the ice-core dated Eldgjá tephra of AD 939 (Sigl et al. 2015; Schmid et al. 2017a), the V-Sv tephra of AD 938 ± 6 (Sigurgeirsson et al. 2013), whose age has been estimated from lacustrine sediment cores, and the historically dated Hekla tephra of AD 1104 (Þórarinsson 1967). 73% ^{14}C samples (n = 377) are stratigraphically associated with widespread tephra isochrons.

Insert Figure 1

Using Iceland as a world-class testing ground for developing ^{14}C synthesis, our aim is to develop a robust and accurate protocol that can be applied to any colonization event and uses the largest number of ^{14}C dates possible, including charcoal samples and bone samples with known marine reservoir effects. This protocol systematically identifies outliers in large ^{14}C datasets within a Bayesian framework using the software OxCal (Bronk Ramsey 2017), as well as tests different *priors* in Bayesian statistical modeling.

2. Methodology: The outlier protocol

We have developed an outlier protocol that can be used to successfully estimate colonization events using small stratified and large unstratified ^{14}C datasets. This protocol involves five steps that are summarized in Figure 2.

Insert Figure 2

Step 1: Define dataset

The first step is to create a set of ^{14}C dates in direct association with cultural materials that define colonization events. For instance, Wilmshurst et al. (2011) included a wide range of ^{14}C dates from 3000 to 300 ^{14}C years BP for the colonization of East Polynesian islands. In our example we used 18 independently dated tephra layers ranging from AD 877 to AD 1693 to define Viking-medieval period settlements and burials (Table 1). In Iceland age estimates of tephra layers – independent of the ^{14}C methods – utilize written sources, correlations with annually layered ice core records in Greenland, as well as annually-laminated lacustrine and aeolian sediment accumulation rates projected over decades (Schmid et al. 2017a). These various age estimates of tephra horizons vary in quality from written sources accurate to the hour, to natural archives with annual to multiannual uncertainties. We have used the following symbols in Table 1: '-' for historically dated tephra, '±' for age independent estimates in ice cores and '~' for estimates from sediment accumulation rates in different depositional environments.

Insert Table 1

We have collected 513 ^{14}C dates that refer to Viking Age settlement and burials sites (AD ~800-1100) (Appendix). Some of the settlement sites are also from the transitional period following the Viking Age.

Step 2: Apply 'chronometric hygiene': remove non-tangible outliers

The next step is to remove dates that cannot be confidently used for statistical analysis, as there is either a high probability that they are inaccurate, or their accuracy cannot be verified. Barrett and Lewis (1978:4) "define an outlier in a set of data to be an observation (or subset of observations) which appears to be inconsistent with the remainder of that set of data". There are two types of outliers: 'non-tangible' (non-statistical) and 'statistical' (samples that are outlying in relation to probability models) (Barrett and Lewis 1978). We define non-tangible outliers as:

1. Inaccurately or published data with insufficient documentation.
2. Bulk sediments.
3. Samples that have inbuilt ages from mixed dietary sources that cannot be adequately corrected.

2.1 Insufficient sample documentation

We have discarded from our analysis age estimates whose publication lacks sufficient metadata. For example, the material dated (e.g. charcoal, seed, bone) is not specified for three ^{14}C dates in the Icelandic dataset. Knowledge of the material type is crucial for Bayesian Outlier analysis, as short-lived samples and samples with inbuilt ages are assigned different *priors* in the model (more information under step 4). Other critical information required for analysis includes stable isotopic data from bone samples, or other information necessary to assess collagen quality (e.g. collagen yield, C:N ratio) (n = 26). Any samples lacking contextual data are labelled 'insufficient metadata' and 'insufficient documentation of isotopic composition' in the folder 'non-tangible outliers' in the Appendix (Table 2).

<u>Insert Table 2</u>

2.2 Bulk sediments

Bulk samples of sediments can contain carbon from multiple sources, with different ^{14}C ratios to the event or context that they are intended to date. Three samples of bulk sediment are excluded from our dataset. They are labelled 'bulk sediments' in the folder 'non-tangible outliers' in the Appendix (Table 2).

2.3 Reservoir offsets

Bone samples whose δ^{13}C values reflect wholly terrestrial atmospheric carbon sources, with no indication of significant admixtures of marine or geologically-derived carbon, are unlikely to have been influenced by any addition of 'old carbon' from reservoirs and normally provide reliable ^{14}C ages.

Organisms growing in ocean surface waters will produce anomalously old ^{14}C ages because of marine reservoir effects, caused by a delay in radiocarbon exchange between the atmosphere and ocean, as well as by the mixing of surface waters with upwelled ^{14}C-depleted deep ocean water (Struiver et al. 1986; Petchey et al. 2008). Organisms that derived some, or all, of their carbon from an oceanic reservoir will have been affected by this marine reservoir effect (MRE).

The 'Marine13' calibration curve represents a global average of the surface ocean ^{14}C as it changes over time (Reimer et al. 2013). However, there are pronounced local deviations from this global average – known as ΔR (Stuiver et al. 1986). In the North Atlantic, for example, ΔR values show spatial and temporal variation (Ascough et al. 2006; Russell et al., 2010). A ΔR value of 111 ± 10 ^{14}C years has been obtained from multiple paired measurements on terrestrial mammals and marine molluscs from Viking Age archaeological deposits in northern Iceland, and is used here (Ascough et al. 2007). Although 111 ± 10 ^{14}C is currently the best estimate, Batt et al. (2015) suggest it could be improved through evaluation of other parts in Iceland.

Omnivorous animals and humans can incorporate carbon from different reservoirs in their diet and may be affected by marine carbon, resulting in an overestimation of their true age (e.g. Arneborg et al. 1999; Ascough et al. 2011; Petchey et al. 2013). δ^{13}C can be used to estimate percentage of marine contribution to the diet using linear interpolation, where values have been established for 100% terrestrial diet and 100% marine diet. For Iceland, the end points can be calculated using the linear regression calculation of Ascough et al. (2012), y =

270.67 + 13.333x, where x is $\delta^{13}C$ value and y is % marine contribution to diet. For the North Atlantic, the $\delta^{13}C$ end values are typically set to -21.0‰ for a terrestrial diet and -12.5‰ for a marine diet (Arneborg et al. 1999; Sveinbjörnsdóttir et al. 2010), with an adjustment of +1‰ for trophic level shift (Ascough et al., 2012). The percentage of marine diet can be included in OxCal using 'Mixed curves' and 'Delta_R' (ΔR).

Freshwater reservoir effects (FREs) also occur when ^{14}C depleted carbon from reservoirs such as peat, old soils or from geothermal activity is added to the freshwater system (Ascough et al. 2010). These reservoirs effects are highly variable, but can amount to many hundreds of ^{14}C years within a single water body, and without extensive regional work, corrections are not possible (Sayle et al. 2016). For example, modern fish from Lake Mýatn in the north of Iceland have radiocarbon reservoirs of more than 3000 ^{14}C years, which vary by around 1500 ^{14}C years (Sayle et al. 2016). Stable isotope analysis of individuals from the nearby cemetery of Hofstaðir suggests they ate just 5-6% freshwater resources, but this would cause offsets of between 40 and 500 ^{14}C years (Sayle et al. 2016). Given the current uncertainties involved in the ^{14}C dating of organisms that have consumed significant amounts of freshwater carbon around Lake Mýatn, 12 dates on shell, four on arctic char and 70 dates on human and animal bone have been excluded from this analysis. The samples are labelled 'uncertain reservoir' in the folder 'non-tangible outliers' in the Appendix.

Step 3: Classify remaining samples according to potential inbuilt age

After having eliminated 118 non-tangible outliers, we categorized all samples according to material classes, for which we use three basic categories:

1. Short-lived taxa: grains, seeds, identified tree bark and twigs and bone samples where the $\delta^{13}C$ values reflect a 100% terrestrial diet
2. Samples with potential or actual inbuilt age: unidentified charcoal and identified heartwood of trees
3. Bone samples that are affected by MRE with known ΔR.

Step 4: Apply Bayesian statistical modeling and define statistical outliers

Bayesian statistical modeling is now routinely used to analyse large sets of ^{14}C dates (Bayliss 2015). The Bayesian approach can be used to test hypotheses, emphasizing that the interpretation of the data is conditional on all of the chronometric information available.

Posterior distributions are generated by modifying *prior* beliefs (e.g. from stratigraphy, assumptions over how outliers are distributed or how dates are distributed across a *Phase*) with *likelihoods* (the ^{14}C dataset).

We used OxCal version 4.3.2 for our analysis (Bronk Ramsey 2017). Here, all terms relating to OxCal are given in *italics*. We used both single-phase and multiple-phase models for our data. For single-phase models, the ^{14}C dates are modelled as a *Phase* – an unordered group of events – bracketed by *Boundaries*, within a *Sequence* – an ordered group of events (Bronk Ramsey, 2009b). This model assumes that all dates are uniformly distributed between the two 'start' and 'end' *Boundaries*. It does not include any stratigraphic relationships between samples from the same site. Where sufficient numbers of radiocarbon dates (>10) were available from a single site, stratigraphic information could be incorporated in a multiple-phase model. The *Boundary* before the *Phase* provides an age estimate for colonization. These *posterior* distributions generate secure *termini ante quos* (TAQs) for archaeological events. Radiocarbon dates are calibrated using the 'IntCal13' curve (Reimer et al. 2013) for the northern hemisphere and the 'Marine13' curve (Reimer et al. 2013) for samples affected by MRE. Throughout the paper, we use both the 68% and 95% *posterior* distributions for *Boundaries*. We used *Agreement Index* and *Outlier models* to assess whether dates are statistical outliers within a model constructed in OxCal.

4.1 The Agreement Index

Originally, models produced in OxCal relied on the *Agreement Index* values ('A' values) to objectively identify outliers. This index quantified the degree to which the data support the proposed model. Values of less than c. 60% indicate a high likelihood (>95%) that there is a problem (Bayliss and Bronk Ramsey 2004). Samples below this value were manually removed until the overall model had an 'A' of >60% (Bronk Ramsey 1995; Bayliss and Bronk Ramsey 2004). This approach is time consuming when dealing with large datasets.

4.2 The General Outlier Model

Bronk Ramsey (2009a) introduced a Bayesian outlier analysis approach, in which the model identifies and downweights dates that are inconsistent with the surrounding data. To do this, the distribution of outliers must be described (the *Outlier Model*), and the prior probability of each sample within this *Outlier Model* assessed. For dates on short lived materials, we use the *General t-type Outlier Model*, which assumes that outlying dates are due to movement between stratigraphic units, and are distributed according to a Student T distribution (Bronk Ramsey, 2009; Christen and Pérez 2009). This is a flexible model, and assumes that although most samples are not outlying a minority may be much too young or much too old. All short-lived materials were given a 5% prior probability of being an outlier within this distribution. The model generates a *posterior* outlier probability for each sample, and downweights the significance of the sample within the model accordingly. For example, a sample found to have an 80% chance of being an outlier will only be included in 20% of the model runs.

4.3 The Charcoal Plus Outlier Model

Some ^{14}C samples can have misleading inbuilt ages, such as those derived from the heartwood of trees with a long-life span or any wood that was utilized long after its death. For example, the first people to settle islands may have burnt old wood from native trees or driftwood collected upon arrival (Sveinbjörnsdóttir et al. 2004). The *Charcoal Outlier Model* (Bronk Ramsey 2009a; Dee and Ramsey 2014), assumes that outliers are most likely to be too old due to their inbuilt age, and that they are derived from an exponential distribution. A small number of samples may be intrusive, and are drawn from an exponential distribution towards younger ages (The *Charcoal Plus Outlier Model*: Dee and Ramsey 2014). In this model all dates are assigned a 100% prior probability of being an outlier, and the effect is to shift the model towards younger ages.

4.4 Assess statistical outliers

Statistical outliers refer to dates that are outlying in relation to probability models. The Icelandic dataset has one clearly anomalous date (St-4192: 260 ± 245 BP) and ten extreme outliers, of which two are exceptionally old (AA-55487: 5179 ± 43 BP and AA-55488: 4110 ± 700 BP) and eight young (HAR-2093: 150 ± 70 BP, U-4030: 305 ± 100 BP, Beta-339966: 520 ± 30 BP, TFG: 565 ± 15 BP and U-2618: 685 ± 110 BP; RKV-SUD U-2535: 810 ± 70 BP, STG K-4488: 840 ± 50 BP and STG K-5366: 800 ± 50 BP). These samples are labelled 'error' or 'extreme outlier' in the folder 'statistical outliers' (Appendix).

We, therefore, conclude that 188 short-lived samples (37 short-lived wood, 34 grains/seeds, and 117 terrestrial bone), 147 samples with inbuilt age (120 long-lived wood, 27 unidentified charcoal) and 49 bone samples that are affected by MRE directly apply to the colonization of Iceland. These 384 samples are in the folder 'other data' (Appendix). All subsequent statistical analyses are based on this assumption.

Step 5: Analysis

The *Difference* function was used to assess whether the *Outlier Models* affect the posterior estimate for the colonization of Iceland. We tested which approach is consistent with the independent tephrochronology using the Landnám Tephra Layer (LTL) of AD 877 ± 1 (Schmid et al. 2017a). In order to be considered different, the *Difference* posterior probability range should not overlap with zero, and the function generates a colonization start *posterior* distribution either earlier or later than the LTL. The results are summarized in Table 3.

<u>Insert Table 3</u>

3. Results

We built Bayesian models using both large unstratified and small stratified ^{14}C datasets. The results are summarized in Table 3 and all OxCal model codes are available in Supplementary Information.

3.1 Unstratified radiocarbon samples

Model 1: Agreement Index (n = 335): The *Agreement Index* was used to assess whether any of the short-lived and charcoal samples were outliers. 18 samples, or 5% of the Icelandic dataset, had an *Agreement Index* < 60% and were manually removed from analysis using the command *Outlier()* (Table 3). The 68% *posterior* distribution for the onset of colonization is estimated to cal AD 851-870, between 11 and 31 years earlier than the LTL.

Model 2: General Outlier Model (n = 335): Each date was assigned an equal prior probability of 0.05 within the *General Outlier Model*. The 68% *posterior* distribution for the onset of colonization extends the range of the calibration curve (Table 3). Samples that were heavily downweighted in this model (assigned a posterior outlier probability of 7-100%) were also identified as outliers using the *Agreement Index* (Table 3).

<u>Insert Table 3</u>

Model 3: General and *Charcoal Plus Outlier Model* (n = 335): We performed analysis using the *General Outlier Model* for short-lived materials (0.05 *prior* probability) and the *Charcoal Plus Outlier Model* for charcoal samples (1 prior probability). The *posterior* distribution for the onset of colonization is estimated to cal AD 863-881 (68%) and to cal AD 751-893 (95%). These age ranges provide a TAQ for the colonization of Iceland consistent with ice-core dated tephrochronology: shortly before, but more likely after AD 877 ± 1 (Fig. 3A).

Insert Figure 3

Model 4: Bone samples affected by MRE (n = 49): We modeled 49 bone samples affected by MRE using the *General Outlier Model*. A 68% *posterior* distribution for the onset of colonization was generated to cal AD 932-973, demonstrating that burials in Iceland are mostly from the late Viking Age.

Model 5: General and *Charcoal Plus Outlier Model* (n = 384): We then combined all 384 samples. The *posterior* distribution for the onset of colonization is estimated to cal AD 815-885 (68%) and to cal AD 733-890 (95%) demonstrating that inclusion of the large number of younger dates on human bone decreases the precision of posterior colonization age estimate (in comparison with Model 3).

Stratified radiocarbon samples

Multiphase models were built for sites where more than ten ^{14}C dates on stratigraphically related samples were available. This approach allows us to determine if samples for dating are likely to be *in situ*, and if there is an 'old wood' problem. It removes difficulties encountered where large numbers of dates fall towards the end of a long single *Phase* (as seen when many relatively young dates on human bone were included in Model 5). Six archaeological sites are stratigraphically above the LTL of AD 877 ± 1 (Reykjavík-Suðurgata, Reykjavík-Aðalstræti, Hrísheimar, Hrísbrú, Skútustaðir, Sveigakot) while two are above the V-Sv tephra of AD 938 ± 6 (Hofstaðir-pit house and Hofstaðir-hall). The estimated *Boundaries* for the start of occupation of each site are shown in Figure 3B.

Model 6: Reykjavík-Suðurgata (n = 14): The site consists of a hall and a smithy built over an activity area which had come into use after the deposition of the LTL. At least four phases of structures were built on top of these remains, before K~1500 blanketed the site (Nordahl, 1988). We excluded samples that are statistical outliers (Table 4). One of the samples used in the model is of short-lived taxa and 13 are charcoal samples. Nine charcoal samples are from early contexts (equivalent to 77% of the whole dataset). The 68% *posterior* distribution is estimated to cal AD 779-897, immediately after the LTL. We demonstrate that a high proportion of charcoal samples can be used in chronological models (here 95%).

Model 7: Reykjavík-Aðalstræti (n = 16): The site consists of a hall that was built on top of the LTL. The K~1500 was deposited long after the hall was abandoned (Sveinbjörnsdóttir et al. 2004). We excluded samples that are statistical outliers (Table 4). Eight samples included in the model are short-lived and eight are charcoal samples. Six samples come from floor and ten from stratified hearth deposits inside the hall. Both deposits are likely contemporary and represent early settlement (equivalent to 100% of the whole dataset). The 68% posterior distribution is estimated to cal AD 802-885, immediately after the LTL. The charcoal samples are consistently older than short-lived materials, but their age offsets are successfully corrected.

Model 8: Hrísheimar (n = 11): The site consists of excavated structures and midden deposits (Vésteinsson and McGovern 2012). Two pit houses and midden deposits are sandwiched between the LTL and V-Sv, while hall structures were built after the deposition of the V-Sv. The model consists of eleven short-lived materials. Two samples come from stratified midden deposits before the V-Sv tephra (equivalent to 16% of the whole dataset), six after this tephra deposit and four are not connected to any tephra layer. The 68% *posterior* distribution is estimated to cal AD 828-881, immediately after the LTL.

Model 9: Sveigakot (n = 18): The site consists of several pit houses, a byre and a hall, as well as extensive midden deposits (Vésteinsson 2010). The model consists of 15 short-lived materials. One sample is from a midden deposit stratigraphically below the V-Sv tephra (equivalent to 7% of the dataset), five samples above the V-Sv tephra (midden and hall) and 12 are from pit houses that are not connected to tephra deposits. The 68% *posterior* distribution is estimated to AD 884-961, or between 3 and 79 *later* than the LTL (Table 3). The 95% *posterior* distribution, however, is estimated to cal AD 848-980 and is consistent with the LTL. The 68% *posterior* distribution is slightly later than the LTL, because the ^{14}C samples are from mid-end tenth century contexts and do not relate to the actual arrival date associated with this initial colonization. Nevertheless 3-79 years are still early in terms of colonization and not every site will have been occupied immediately after the deposition of the LTL.

Model 10: Skútustaðir (n = 17): The site consists of a farm mound with several structures and well-stratified midden deposits (Hicks et al. 2013). The middens began to form immediately on top of the LTL and accumulation has persisted until modern times. The model consists of 12 short-lived materials. One ^{14}C sample is below the V-Sv tephra (equivalent to 6% of the whole dataset), 12 samples are above the V-Sv tephra and four samples are not associated with any tephra layer. The 68% *posterior* distribution is estimated to cal AD 838-938, consistent with the LTL.

Model 11: Hrísbrú (n = 11): The site consists of a hall, midden deposits, a church and multiple burials. The model consists of eleven stratified samples, of which ten are short-lived and one charcoal sample. Although anthropogenic deposits at Hrísbrú are stratigraphically above the LTL, all ^{14}C samples are from contexts that also post-date a tenth century tephra (either K~920 or Eldgjá) (Schmid et al. 2017b). Four samples are from upper floor layers under a turf collapse (representing the last use of the house) and another four samples come from the midden deposits on top of the hall. One sample is from the church, which was built after the deposition of a tenth century tephra and two samples are from midden deposits from before the church was constructed. The 68% *posterior* distribution is estimated to cal AD 889-950, or between 11 and 70 years *later* than the LTL; the 95% *posterior* distribution, however, is estimated to cal AD 867-965 and is consistent with the LTL (Table 3). This 68% *posterior* distribution is slightly later than the LTL because all ^{14}C samples are from mid-end tenth century contexts (like Model 9) and do not relate to the actual arrival date associated with this initial colonization.

Model 12: Hofstaðir-pit house (n = 11): The site consists of a pit house infilled with stratified midden deposits. The pit house is sandwiched between the V-Sv and H-1104 tephras (Lucas 2009). The site consists of eleven short-lived samples. One sample is from the turf collapse of the pit house, the rest are from the midden layers. The 68% *posterior* distribution is estimated to cal AD 874-948 and consistent with the LTL, and also with the V-Sv tephra.

Model 13: Hofstaðir-hall (n = 13): The site consists of a hall with annexes that are sandwiched between the V-Sv and H-1104 tephras (Lucas 2009). The samples are from floor layers and from the turf collapse on top of the floor. The model consists of eleven short-lived materials and none are from early settlement contexts. The *posterior* distribution is estimated to cal AD 951-988 (68%) and to cal AD 915-1009 (95%), or up to 127 years *later* than the LTL (Table 3). This *posterior* distribution is, however, consistent with the V-Sv tephra, which is not surprising, because the ^{14}C samples come from mid-end tenth century contexts.

We then combined the *posterior* distributions produced above to determine the most likely timing of overall colonization. This approach can also be used for comparing *posterior* distributions and determining the spatiotemporal relationships between archaeological sites across the country.

Model 14: Priors of archaeological sites: Eight archaeological sites yielded an age range of cal AD 799-864 (68%), or between 17 and 83 years earlier than the LTL; the 95% *posterior* distribution, however, is estimated to cal AD 728-880 and is consistent with the LTL (Table 3).

Model 15: Priors of archaeological sites including LTL and V-Sv tephra: We can constrain the same dataset (Model 14) when we include the LTL as *Calendar Date* (*C_Date*). The tephra layers constrain the *posterior* distribution to cal. AD 875-883 (68%) and to cal AD 870-894 (95%); however, this model can only be applied in geographic areas where tephra layers exist (Fig. 3C).

4. Discussion

Using the colonization of Iceland as a critical test of ^{14}C methodology, we find that stratified archaeological sites with more than ten ^{14}C samples provide an age estimate for colonization, which is consistent with ice-core dated tephrochronology, and thus deemed accurate, providing that appropriate *prior* assumptions are used and the distribution of ^{14}C dates through the *Phase* is uniform. As such, *General Outlier Models* could be used with confidence to create chronologies from multiple ^{14}C dates on short-lived plant materials, terrestrial bone, and bone affected by marine reservoir effects. *Charcoal Plus Outlier Models* can be used with confidence for synthesizing sets of ^{14}C dates based on wood/charcoal with inbuilt age. Furthermore, our new assessments have demonstrated that that Bayesian models are sensitive to the uniform *prior* assumption. First, the inclusion of the large number of younger dates decreases the precision of posterior colonization age estimate (e.g. Model 5), because there is a comparable lower density of data towards the start of a *Phase* (I comparison to Model 3). Second, if dates from early contexts are removed, the *posterior* colonization age estimate will most likely underestimate early human activity (Models 4, 9 and 11).

The dating of island colonization in Oceania has undergone radical reassessment since the 1980s (Dye 2015). These cases exemplify critical debates about colonization and chronology all over the world. Competing ‘long’ and ‘short’ chronologies of island settlement have been proposed that are based on selective ^{14}C datasets, which have been filtered using differing 'chronometric hygiene protocols'. In this paper, we show that a new outlier protocol can provide a reduced need for the initial rejection of ^{14}C dates compared to previous protocols. We argue that it is preferable to only exclude a minimum number of samples, where key information about e.g. context, sample type and pre-treatment quality, is unpublished, or where it is very likely that accuracy is poor e.g. for sediment or bone affected by a FRE. On this basis, 129 out of 513 samples (24%) were removed from analysis. We note that some of the samples may have potential to be used for future studies, if additional metadata is forthcoming.

Elsewhere, we (Schmid et al. 2018) have reviewed the ^{14}C data from 15 archipelagos in East Polynesia (published in Wilmshurst et al. 2011). While independent dating control is generally absent in Oceania, the North island of New Zealand is an exception. Here, environmental impacts and human activities first occur just below the Kaharoa tephra isochron, which is radiocarbon-dated to cal AD 1314 ± 12 through the use of wiggle matching (Hogg et al. 2002). We have synthesized 265 ^{14}C dates using a combination of short-lived plant materials, terrestrial bone, and (un-)identified charcoal and generated a *posterior* distribution for colonization of cal AD 1260-1314 (68%), which is consistent with the stratigraphic distribution of palaeoenvironmental evidence related to the Kaharoa isochron. Both in Iceland and East Polynesia, the inclusion of a wider range of ^{14}C samples in Bayesian models improves the precision of the combined age determination. Significantly, the inclusion of tephra layers in chronological models does not affect the accuracy of the model outcome (e.g. Model 15). Thus, we find that our chronometric hygiene protocol may be usefully applied elsewhere and in areas where tephra isochrons are absent. The utilization of a wide range of samples benefits chronological models, because it most likely captures initial phases of settlement, enhances precision and dating can be applied more widely, especially relating to the chronology in coastal areas and on small islands.

5. Conclusion

This study uses a clearly defined and independently dated archaeological event – the initial human colonization of Iceland – to evaluate the best ways to assess small stratified (> 10) and large unstratified (> 280) ^{14}C datasets based on the analysis of different materials, and to identify the most parsimonious exclusion of dates from synthesis. We demonstrate that, when combined with appropriate *priors* in *Outlier Models* within OxCal, ^{14}C dates on the majority of sample types, most notably charcoal with its potential inbuilt age and samples affected by marine reservoir effects, can be used in chronological models. At present, dates produced on samples with insufficient metadata (e.g. no published record of material types or stable isotope values) or samples affected by unknown freshwater reservoir effects cannot be used. This result is important because it shows that a greater range of materials than currently accepted might be used with confidence for ^{14}C analysis provided that certain conditions are met including the dissemination of contextual data (including detailed sample metadata), which have to be fully published.

Figures

Fig. 1 The distribution of archaeological sites in stratigraphic relationships to the Landnám Tephra Layer (LTL) on a countrywide scale (**a**) and on a regional scale around Reykjavík (**b**), Skagafjörður/Langholt (**c**) and Mývatn (**d**). Two sites are below the LTL (stars) and 85 settlement sites (dots) as well as 181 related radiocarbon dates from 35 burial and settlement sites are above this tephra isochron (crosses). Archaeological sites that are discussed in this paper are: (**a**) **A**. Reykjavík-Suðurgata, **B**. Reykjavík-Aðalstræti, **C**. Hrísbrú; (**c**) **D**. Hrísheimar, **E**. Sveigakot, **F**. Skútusstaðir, **G**. Hofstaðir-pit house and **H**. Hofstaðir-hall.

Fig. 2 Outlier protocol for ^{14}C datasets demonstrating the importance of stratigraphic relationships of ^{14}C samples. Bayesian *Outlier Models* will be affected if ‘chronometric hygiene’ protocols preferentially remove dates from early contexts. Key: B-M: Bone-Marine, B-T: Bone-Terrestrial, G/S: Grains/Seeds, LL: Long-Lived, MRE: Marine Reservoir Effect, SL: Short-Lived, W-SL: Wood-Short-Lived.

Fig. 3 Estimated *posterior* distributions for the timing of Iceland’s colonization using unstratified (A) and stratified (B) datasets (95.4% probability curves). **A**. The combination of 190 short-lived and 144 charcoal samples (n = 335). **B**. Multiple stratified ^{14}C samples from eight archaeological sites (>10). The *posterior* distribution is constrained by the LTL to cal AD 874-883.

Table 1 Tephrostratigraphy in Iceland. The tephra layers are named after the source volcanic system and the eruption date in years AD. The volcanic source systems are: E: Eldgjá, G: Grímsvötn, H: Hekla, K: Katla, Ö: Öræfajökull, R: Reykjaneshryggur and V: Veiðivötn.

Name of tephra layer	*Year AD*	*Dating method*	*References*
LTL	877 ± 1	Greenland ice cores	Grönvold et al. 1995; Zielinski et al. 1997; Schmid et al. 2017a
K~920	~920	Sediment accumulation rates	Hafliðason et al., 1992
V-Sv	938 ± 6	Sediment accumulation rates	Sigurgeirsson et al. 2013; Schmid et al. 2017a
Eldgjá	939	Greenland ice cores	Sigl et al. 2015; Schmid et al. 2017a
Vj	~1000	Sediment accumulation rates	Sigurgeirsson, 2010
H-1104	1104	Historical date	Þórarinsson, 1967
H-1158	1158	Historical date	Þórarinsson, 1967
V-1159	1159	Historical date	Hafliðason et al. 2000
H-1209	1209	Historical date	Þórarinsson 1967
R-1226	1226	Historical date	Hafliðason et al. 1992
K-1262	1262	Historical date	Þórarinsson 1975
H-1300	1300	Historical date	Þórarinsson 1967
G~1320	~1320	Sediment accumulation rates	Þórarinsson 1974
H-1341	1341	Historical date	Þórarinsson 1967
Ö-1362	1362	Historical date	Þórarinsson 1958
V~1477	~1477	Sediment accumulation rates	Þórarinsson 1958
K~1500	~1500	Sediment accumulation rates	Hafliðason et al. 1992
H-1693	1693	Historical date	Þórarinsson 1967

Table 2 'Chronometric hygiene': 513 ^{14}C dates and their reason for exclusion/inclusion in chronological models. Statistical outliers were identified using *Agreement Indices* (> 60% cut off) and *General Outlier models*.

Outlier type	*Reason*	*Description*	*Excluded [E] Included [I]*	*Erroneous dates?*	*Number of samples*
Non-tangible outliers	Insufficient metadata	Material types are not published	E	Not possible to assess	3
Non-tangible outliers	Insufficient documentation of isotopic composition	Isotopes are not published	E	Not possible to assess	26
Non-tangible outliers	Bulk sediment	-	E	Mixed carbon	3
Non-tangible outliers	Unknown reservoirs	Marine and freshwater contribution to diet	E	No, however, very high probability that these samples show freshwater contribution to diet (samples are from contexts around lake Mývatn)	86
Statistical outliers	Anomalously old or young	Contamination?	E	Yes, because they lie outside the distribution probability	10
Statistical outliers	Erroneous	Contamination?	E	Yes, because the date is erroneous	1
Other	Potentially 'accurate' dates	Viking Age contexts	I	If charcoal samples, they do not date the event in question. If samples are	335

				short-lived, the date can represent human activity (unless the samples is contaminated, e.g. PVA)	
Other	Potentially 'accurate' dates with marine reservoir offsets	Viking Age contexts	I	Potential freshwater reservoir offsets (samples are from contexts that are not close to lake Mývatn)	49

Table 3 Sensitivity testing of single- and multiple-phase models from Iceland evaluating potentially accurate dates using the *Agreement Index* (> 60% cut off), *General Outlier models* and *Charcoal Plus Outlier models* (greater than 7% outlying).

Approach number	*Approach detail*	*Nr ^{14}C*	*Boundary (1σ)*	*Boundary (2σ)*	*Difference to LTL in years (1σ): from*	*Difference to LTL in years (1σ): to*	*Difference to LTL in years (2σ): from*	*Difference to LTL in years (2σ): to*	*Short-lived %*	*Early contexts %*
1	Agreement Index	317	851-870	797-876	-31	-11	-82	-2	60	57
2	General Outlier Model	335	753-…	736-…	-88	…	-82	…	56	54
3	General Charcoal Plus Outlier Model	335	863-881	751-893	-20	1	-128	12	56	54
4	General Outlier Model	49	932-973	893-991	49	93	11	112	100	0
5	General Charcoal Plus Outlier Model	384	815-885	733-890	-65	7	-134	11	62	47
6	Reykjavík-SUD	20	779-897	779-897	-102	17	-180	75	5	77
7	Reykjavík-AST	16	802-885	723-895	-68	4	-140	14	50	100
8	Hrísheimar	13	828-881	758-893	-57	2	-135	14	100	16
9	Sveigakot	18	884-961	848-980	3	79	-33	100	100	6
10	Skútustaðir	17	838-938	803-954	-46	59	-80	74	100	6
11	Hrísbrú	10	889-950	867-965	11	70	-16	86	100	0
12	Hofstaðir pit house	11	874-948	810-969	-6	68	-70	89	100	0
13	Hofstaðir hall	13	951-988	915-1009	99	127	85	138	100	0
14	Archaeological sites prior	118	799-864	728-880	-83	-17	-150	0	/	/
15	Archaeological sites prior including LTL and V-Sv tephra	118	875-883	870-894	/	/	/	/	/	/

Table 4 Identified outliers using the *Agreement Index* (18 samples) and *General Outlier model* (21 samples). Outliers identified in Bayesian models using the *Agreement Index* are below 60%, while outliers identified in *General Outlier models* are between 6 and 100% outlying (posterior probability).

Site name	*Sample ID*	*Conventional Radiocarbon Age*	*Error*	*Associated tephra deposit (after Schmid et al. 2017a)*	*Agreement Index*	*General Outlier Model*
Herjólfsdalur (Vestman island)	U-2660	1390	60	post-LTL	< 60%	44%
Herjólfsdalur (Vestman island)	U-2661	1340	65	post-LTL	< 60%	13%
Herjólfsdalur (Vestman island)	U-2663	1300	60	post-LTL	< 60%	9%
Hólmur	Beta-143635	1450	70	post-LTL	< 60%	69%
Reykjavík: Althingisreiturinn	Beta-346805	1295	25	Between LTL and R-1226	< 60%	46%
Reykjavík: Aðalstræti 14-18	AAR-7619	1282	35	Between LTL and H-1500	< 60%	19%
Reykjavík: Aðalstræti 14-18	AAR-7622	1262	35	Between LTL and H-1500	< 60%	9%
Reykjavík: Aðalstræti 14-18	K-940	1340	100	post-LTL	< 60%	17%
Reykjavík: Aðalstræti 14-18	U-2530	1330	80	post-LTL	< 60%	8%
Reykjavík: Grjótagata	K-949	1340	100	post-LTL	< 60%	7%
Reykjavík: Suðurgata 3-5	U-2672	1345	60	Between LTL and H-1500	< 60%	17%
Reykjavík: Suðurgata 3-5	U-2676	1260	55	Between LTL and H-1500	< 60%	6%
Reykjavík: Suðurgata 3-5	U-2680	1375	70	post-LTL	< 60%	21%
Reykjavík: Suðurgata 3-5	U-2719	1360	60	Between LTL and H-1500	< 60%	24%
Reykjavík: Suðurgata 3-5	U-2739	1310	70	post-LTL	< 60%	8%
Reykjavík: Suðurgata 3-5	U-2740	1280	65	Between LTL and H-1500	< 60%	6%
Reykjavík: Suðurgata 3-5	U-2741	1330	40	post-LTL	< 60%	39%
Reykjavík: Suðurgata 3-5	U-2745	1275	60	Between LTL and H-1500	< 60%	6%

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Author Contributions Statement

MMES designed research; MMES performed research and analysed data; MMES and AJN collected the GIS data; MMES and AJN created the figures; and MMES, AJD, AJN, OV and RW wrote the paper.

Additional Information

Competing financial interests

The author(s) declare no competing financial interests.

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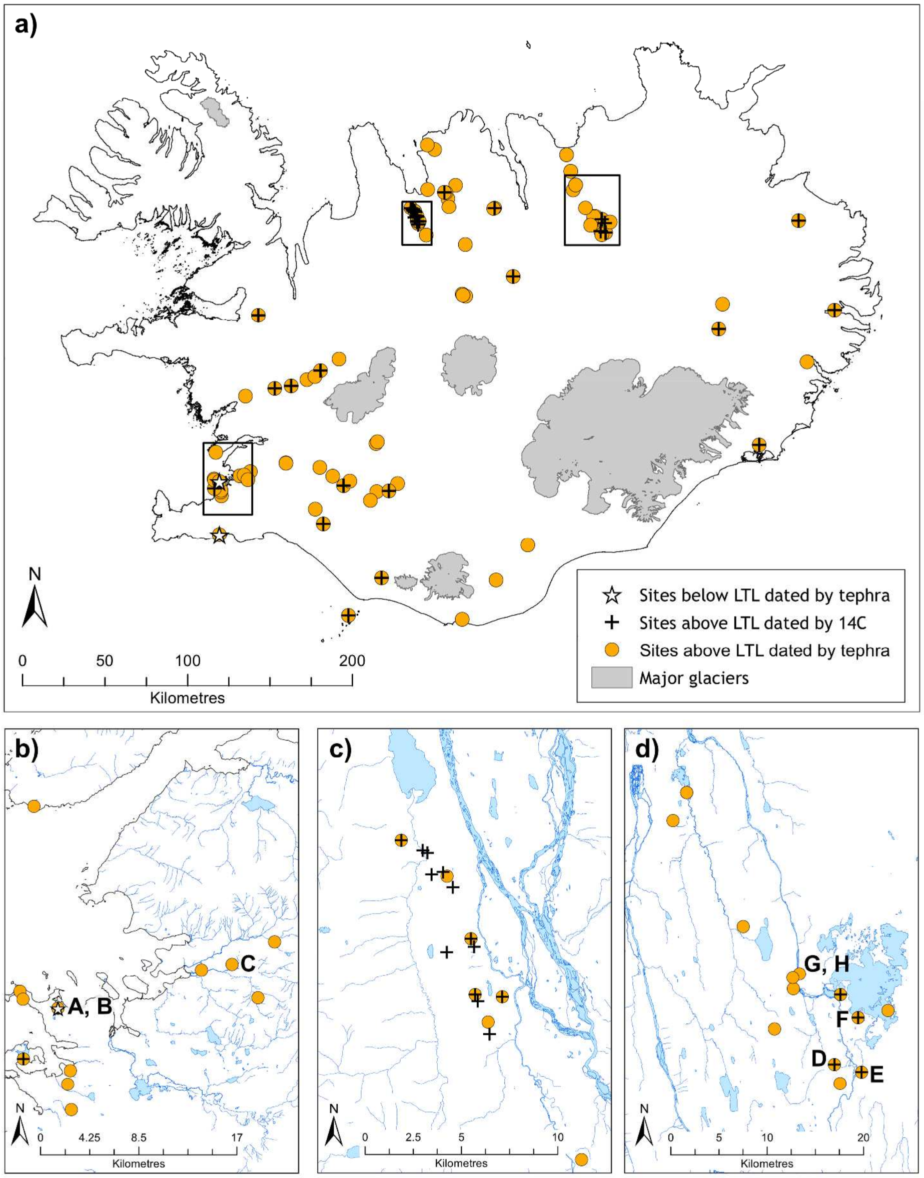

Fig. 1 The distribution of archaeological sites in stratigraphic relationships to the Landnám Tephra Layer (LTL) on a countrywide scale (a) and on a regional scale around Reykjavík (b), Skagafjörður/Langholt (c) and Mývatn (d). Two sites are below the LTL (stars) and 85 settlement sites (dots) as well as 181 related radiocarbon dates from 35 burial and settlement sites are above this tephra isochron (crosses). Archaeological sites that are discussed in this paper are: (a) A. Reykjavík-Suðurgata, B. Reykjavík-Aðalstræti, C. Hrísbrú; (c) D. Hrísheimar, E. Sveigakot, F. Skútusstaðir, G. Hofstaðir-pit house and H. Hofstaðir-hall.

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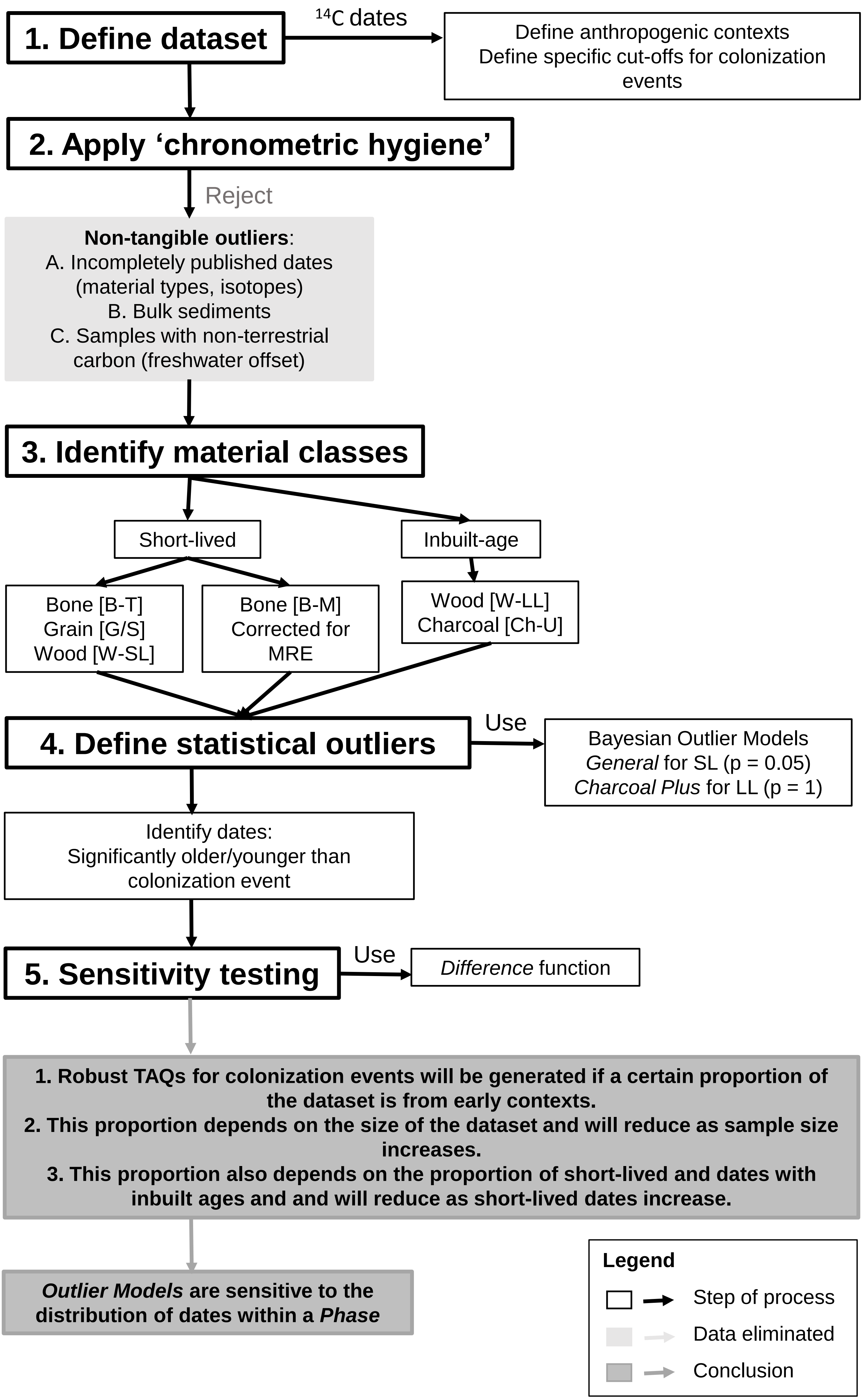
1. Define dataset
14C dates
Define anthropogenic contexts
Define specific cut-offs for colonization events
2. Apply 'chronometric hygiene'
Reject
Non-tangible outliers:
A. Incompletely published dates (material types, isotopes)
B. Bulk sediments
C. Samples with non-terrestrial carbon (freshwater offset)
3. Identify material classes
Short-lived
Inbuilt-age
Bone [B-T]
Grain [G/S]
Wood [W-SL]
Bone [B-M]
Corrected for MRE
Wood [W-LL]
Charcoal [Ch-U]
4. Define statistical outliers
Use
Bayesian Outlier Models
General for SL (p = 0.05)
Charcoal Plus for LL (p = 1)
Identify dates:
Significantly older/younger than colonization event
5. Sensitivity testing
Use
Difference function
1. Robust TAQs for colonization events will be generated if a certain proportion of the dataset is from early contexts.
2. This proportion depends on the size of the dataset and will reduce as sample size increases.
3. This proportion also depends on the proportion of short-lived and dates with inbuilt ages and and will reduce as short-lived dates increase.
Outlier Models are sensitive to the distribution of dates within a Phase
Legend
Step of process
Data eliminated
Conclusion

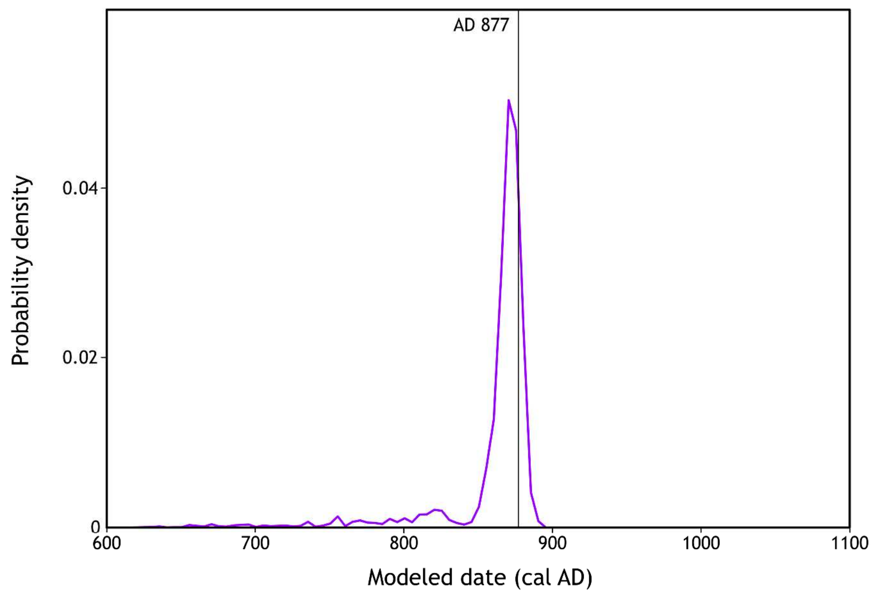

Fig. 3 Estimated posterior distributions for the timing of Iceland’s colonization using unstratified (A) and stratified (B) datasets (95.4% probability curves). A. The combination of 190 short-lived and 144 charcoal samples (n = 335). B. Multiple stratified 14C samples from eight archaeological sites (>10). The posterior distribution is constrained by the LTL to cal AD 874-883.

1411x911mm (72 x 72 DPI)

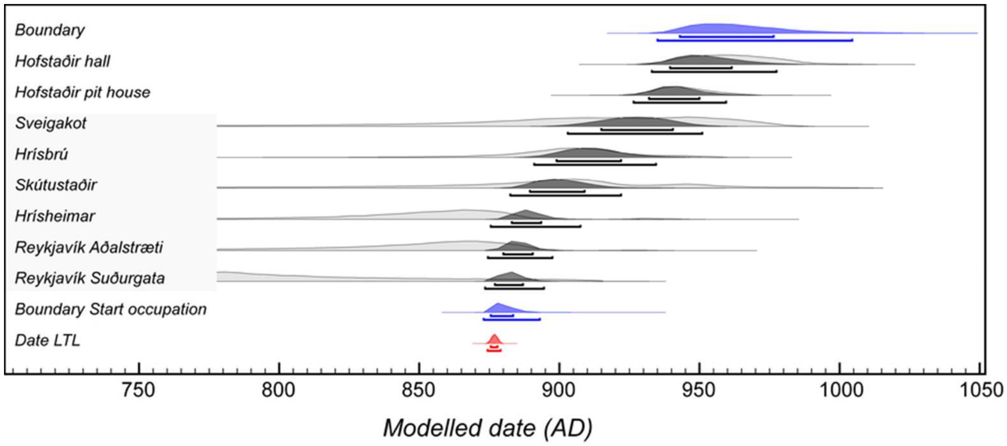

Fig. 3 Estimated posterior distributions for the timing of Iceland's colonization using unstratified (A) and stratified (B) datasets (95.4% probability curves). A. The combination of 190 short-lived and 144 charcoal samples (n = 335). B. Multiple stratified 14C samples from eight archaeological sites (>10). The posterior distribution is constrained by the LTL to cal AD 874-883.

76x33mm (300 x 300 DPI)